nature of cellular transmission (call duration) and the improbability that a person would remain a few centimeters from the antenna for an extended length of time would make such worst-case exposure unlikely. The University of Washington study also indicated that vehicle occupants are effectively shielded by the metal body of the car.

D. Comparison With Safety Standards and Guidelines

A comparison of the above data can be made with the maximum allowable local SAR specified in several existing U.S. RF safety standards and guidelines. When compared with these limits, the SAR measurements and incident power densities of portable and mobile transceivers and telephones show that in most cases the levels are well below those recommended in the standards. However, one of these studies (Cleveland and Athey, 1989) showed that the 8 W/kg level might be exceeded for a hand-held transceiver operating in the 800 MHz band and at 3 W or more, if the antenna feed-point was very close (1 cm or less) from the user's head or eyes. If the 1.6 W/kg for the uncontrolled environment is used as a threshold, the mobile transceiver might produce SARs that exceed this level under worst-case conditions. But, once again, when the relevant time-averaging period of 30 min. is considered, the actual exposure associated with these transceivers would probably not exceed the guidelines.

For cellular vehicle-mounted transceivers, the 1982 ANSI exposure limits used by the FCC are not exceeded, even in cars with the smallest dimensions, if the cellular antenna is mounted more than 15 cm from the passengers. In the majority of situations, the maximum exposure from cellular phones is 10 times lower than the standards used by the FCC.

E. Conclusions

Data from engineering studies indicate that in most cases SARs associated with the use of hand-held commercial cellular transportable and mobile transceivers and telephones do not exceed the maximum permissible levels specified in existing RF safety standards and guidelines. Therefore, under conditions of normal use, the general conclusion is that cellular telephones are considered safe for the users and the public. Some non-cellular mobile transceivers may emit high intensity fields for which prolonged exposure near the antenna could exceed safety criteria. The safety of these devices must be assessed on an individual basis.

REFERENCES

1. ACGIH, (1986). American Conference of Governmental and Industrial Hygienists, Threshold Limit Values.

2. ANSI-C95.1, (1982). "Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 300 kHz to 100 GHz." American National Standards Institute, N.Y., N.Y.

3. Balzano, Q., Garay, O., Steel, F.R. (1977). Energy deposition in biological tissue near portable radio transmitters at VHF and UHF. Conference Record of the 27th Annual Conference, IEEE Vehicular Technology Group, Orlando, FL, 25-39.

4. Balzano, Q., Garay, O., Steel, F.R. (1978a). Heating of biological tissue in the induction field of VHF portable radio transmitters. IEEE Trans. Veh. Tech. VT-27(2): 51-56.

5. Balzano, Q., Garay, O., Steel, F.R. (1978b). Energy deposition in simulated human operators of 800-MHz portable transmitters. IEEE Trans. Veh. Tech. VT-27(4): 174-181.

6. Balzano, Q., Garay, O., Steel, F.R. (1979). An attempt to evaluate the exposure of operators of portable radios at 30 MHz. Conference Record of the 29th Annual Conference, IEEE Vehicular Technology Group, Arlington Heights, IL, March 27-30, 187-188.

7. Balzano, Q, Garay, O. (1984). Dyna TAC exposure measurements. Motorola Report, May 15. Available from Dr. Balzano at Motorola.

8. Balzano, Q., Garay, O., Manning, T. (1986). RF energy in cars from window-mounted antennas. Conference Record of the 36th Annual Conference, IEEE Vehicular Technology Group, Dallas, TX, 32-40.

9. Chatterjee, I., Gu, Y., Gandhi, O.P. (1985). Quantification of electromagnetic absorption in humans from body-mounted communication transceivers. IEEE Trans. Veh. Tech. VT-34(2): 55-62.

10. Cleveland, Jr., R.F., Athey, T.W. (1989). Specific absorption rate (SAR) in models of the human head exposed to hand-held UHF portable radios. Bioelectromagnetics 10: 173-186.

11. DOD, (1986). Department of Defense Instruction Number 6055.11, "Protection of DOD Personnel from Exposure to Radiofrequency Radiation," August 20.

12. Guy, A.W., Kramer, P.O., Harris, C.A., Chou, C.K. (1980). Long Term 2450 MHz CW Microwave Irradiation of Rabbits: Methodology and Evaluation of Ocular and Physiologic Effects. J. Microwave Power 15(1): 37-44.

13. Guy, A.W., Chou, C.K. (1986). Specific Absorption rates of energy in man models exposed to cellular UHF-mobile-antenna fields. IEEE Trans. Microwave Theory and Techniques, MTT-34(6): 671-680

14. IEEE C95.1-1991 (1992). "Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz," Piscataway, NJ: IEEE.

15. IRPA, (1988). Guidelines on limits of exposure to radiofrequency electromagnetic fields in the frequency range from 100 kHz to 300 GHz, Health Physics, 54(1): 115-123.

16. Johnson, C.C., Guy, A.W. (1972), Nonionizing Electromagnetic Wave Effects in Biological Materials and Systems. Proc. IEEE. Vol. 60: 692-718

17. Kramar, P.O., Emery, A.F., Guy, A.W., Lin, J.C. (1975). The ocular effects of microwaves on hypothermic rabbits: a study of microwave cataractogenic mechanisms. Ann. of N.Y. Academy of Science, 247: 155-165.

18. Kuster, N., Balzano, Q. (1992) Energy absorption mechanism by biological bodies in the near field of dipole antenna above 300 MHz. IEEE Trans. Veh. Tech. VT-41(1): 17-23.

19. Motorola (1987). Comments to FCC. Second Report and Order, Gen. Docket 79-144, Federal Communications Commission, Washington, D.C. (1987). 52 Federal Register 13240, 2 FCC Record 2064, 2 FCC Record 2526.

20. NCRP (1986). Biological effects and exposure criteria for radiofrequency electromagnetic fields, Report 86, (Bethesda, MD: National Council of Radiation Protection and Measurements) 1-382.

TAB C

Bioelectromagnetics 13:527–542 (1992)

Radio-Frequency Electromagnetic Fields Associated With Cellular-Radio Cell-Site Antennas

R.C. Petersen and P.A. Testagrossa

Radiation Protection Department, AT&T Bell Laboratories, Murray Hill, New Jersey

Because of a heightened public awareness of issues pertaining to the use of electromagnetic energy, concurrent with a rapid growth of the cellular telephone industry, a study was initiated to characterize the electromagnetic environment associated with typical cell-site antennas. In particular, the radio-frequency electromagnetic (RF) fields in the vicinity of several antenna towers, ranging in height from 46–82 m, were characterized by measurement. In all cases, the antennas were omnidirectional co-linear arrays. The maximal power densities considered representative of public exposure were found to be less than 100 μW/m^2 (10 nW/cm^2) per radio channel. Comparison of measured values with the corresponding values that were calculated from the free-space transmission formula indicated that the analytical technique is conservative (i.e., overestimates field levels). The measured and corresponding analytical values were found to be well below accepted exposure limits even when extrapolated to simultaneous and continuous operation of the maximal number of transmitters that would be expected to be installed at a cell-site. Additional measurements were made in the near field of the same antenna type in a roof-mounted configuration. At a distance of 0.7 m from the antenna, the maximal power density in the main beam was found to be less than 30 W/m^2 (3 mW/cm^2) when normalized to sixteen radio channels (the maximal number used on a single antenna) and less than 30 mW/m^2 (3 μW/m^2) at 70 m. In all cases, the effective radiated power (ERP) by each radio channel was 100 W referenced to a half-wave dipole. This paper describes the instrumentation and measurement techniques used for this study and provides a summary of the results. © 1992 Wiley-Liss, Inc.

Key words: microwave, cellular-radio, potential exposure, electromagnetic environment

INTRODUCTION

Unlike conventional mobile radio-telephone systems by which a large service area is uniformly covered by a few radio channels, cellular radio, which operates in the 800–900 MHz band, offers enhanced service by dividing a service area into smaller areas, called cells, and reusing frequencies in nonadjacent cells. Each cell, with its own base station or *cell-site*, provides the radio interface between the system and the mobile units. The cell-site consists of the antennas, radios, and switching

Received for review January 10, 1992; revision received May 4, 1992.

Address reprint requests to R.C. Petersen, AT&T Bell Laboratories, Room 1F-101C, Murray Hill, NJ 07974.

equipment necessary for connecting mobile units within the cell to the rest of the network. The cells are connected, typically by land line or microwave radio, to a mobile telephone switch office, which is connected to the telephone network. The system tracks each active mobile or portable unit within each cell and sets up a call as soon as it is requested. As the mobile unit travels from one cell to another, the system automatically "hands off" the call to the next cell without perceptible interruption. Because the system uses frequency modulation (FM) and operates at low power levels, the same frequencies may be reused in nonadjacent cells, thereby increasing the capacity of the system. Further, as the system expands, the cells may be subdivided and the capacity increased even more. Because of user acceptance, systems in most areas are currently undergoing major expansion, and as a result cells are being subdivided, particularly in suburban areas. This need for additional cell sites, with the concomitant antenna structures becoming more prominent within communities, has led to an increase in public concern about exposure to the electromagnetic fields from these antennas.

Although there are several different systems currently in use or being installed in the US, for purposes of this study the differences are relatively unimportant. For example, while one system may have a capacity of 72 transmitters at a cell site and another system 96, the measurement results presented here have been normalized on a per channel basis. (Although the term *channel* usually refers to a specific, narrow band of frequencies, there is an individual transmitter for each channel and, therefore, the terms *channel* and *transmitter* will be used interchangeably.) Also, few, if any, cell-sites operate anywhere near capacity or have the maximal number of radios installed. For purposes of illustration, a system with a maximum of 96 transmitters will be described as a worst-case scenario.

A start-up cell, with a typical radius of 12–16 km, is usually serviced by omnidirectional (in the horizontal plane) antennas located at the center of the cell. These antennas are co-linear arrays approximately 4 m in overall length. The gain is typically 9 or 10 dB over a half-wave dipole. A maximum of 16 transmitters may be connected to a single antenna. The output power of each transmitter is such that the per channel effective radiated power (ERP)—that is, the product of the antenna input power and the antenna gain—is 100 W or less. Thus, the actual level of radiation is of the order of 10 W per channel. The cell-site transmitter frequencies are between approximately 869 and 894 MHz, depending on the frequency plan used. (The frequencies of mobile units are between 824 and 850 MHz.)

The antennas may be mounted on towers, rooftops, water tanks or any other structure that provides the necessary height. Frequently, freestanding towers (monopoles) approximately 45 m tall are used. The antennas are normally installed on a triangular platform that is mounted in the horizontal plane at the top of the tower. Each face of the platform is approximately 3 m long. The transmitting antennas are usually mounted above the platform, the receiving antennas below. Up to seven transmitting antennas can be installed, one of which is connected to a lower power transmitter called the setup (or paging) transmitter (channel), which is used for location and signaling. Thus, up to 96 voice channels may be accommodated using this configuration.

When the cells are divided, directional antennas are usually used. These antennas, which are rectangular shaped, approximately 0.6 m wide and 1.2 m high with a gain of approximately 8–12 dB (depending on the antenna), are usually mounted to the faces of the triangular platform at the top of towers or on the sides of buildings, water tanks, and similar structures. A fully expanded cell-site utilizing directional antennas (usually referred to as sector antennas) could have two transmitting antennas on each platform face (each with up to 16 radio transmitters) and two receiving antennas. An omnidirectional antenna is usually used for the setup (paging) channel and one or two omnidirectional antennas for the setup receivers. To prevent interference with remote cells using the same frequencies, the sector antennas are sometimes slightly downtilted and/or the transmitter power is reduced. Thus, the maximal number of radios transmitting in any specific direction for the sector configuration is 32 along the axis of the antenna and up to 64 where the patterns of two antennas overlap.

The purpose of this study is to document the potential levels of exposure to radio-frequency energy in the vicinity of typical cellular installations including tower- and roof-mounted antennas. The results of the measurements made near the base of typical towers indicate that theoretical methods commonly used for estimating the upper bound of the power density [Shinn, 1976; Stuchly, 1977; NCRP, 1981], at ground level for example, are conservative. The results of the rooftop measurements provide insight into expected levels in the near-field of typical omnidirectional antennas used for cellular service.

TOWER-MOUNTED ANTENNA MEASUREMENTS

Cell-site antennas may be mounted on freestanding towers, either lattice type (constructed of crossed structural-steel members) or monopoles (a tapered steel column, circular in cross-section), guyed towers, (towers supported by steel cables), water tanks, chimneys, the sides of buildings, rooftops, or similar structures of sufficient elevation to provide adequate cell coverage. The height of the antennas is important in that they must be sufficiently high to provide adequate coverage, but cannot be excessively high or interference with remote cells may occur. Commonly used ground-mounted masts (monopoles) range in height from less than 12 m to over 45 m, with 45 m being common. Lattice-type towers can be as high as 85 m, or even higher. In this study, the electric-field strength was measured near the base of two typical monopoles (45 m and 50 m) and two lattice towers (66 m and 83 m). In each case, the transmitting antennas were omnidirectional co-linear arrays with a gain of 9 or 10 dB relative to that of a half-wave dipole (Decibel Products DB809, DB810, or equivalent). The nominal ERP per channel was 100 W. The vertical, far-field radiation pattern of a typical omnidirectional cell-site antenna is shown in Figure 1.

The test antenna used for the measurements was either a tunable dipole (Electrometrics TDS-25-2) or a conical log-spiral antenna (Singer Stoddart 934901-1 or 93491-2). The Singer Stoddart (SS) 93491-2, which is normally used for frequencies between 1 and 10 GHz, was calibrated in a known linearly polarized field at 880 MHz and was preferred over the physically larger lower frequency (0.2 to 1 GHz) antenna (SS 934901-1). The majority of the measurements, however, were made with the tuned dipole. In all cases, the antenna was mounted on a wooden tripod at a height of approximately 2 m. The antenna cable was either 6.1 or 12.2 m of Storm Products Co., Series 90 flexible coaxial cable with a measured loss of 1.2 and 2.4 dB, respectively, at 880 MHz.

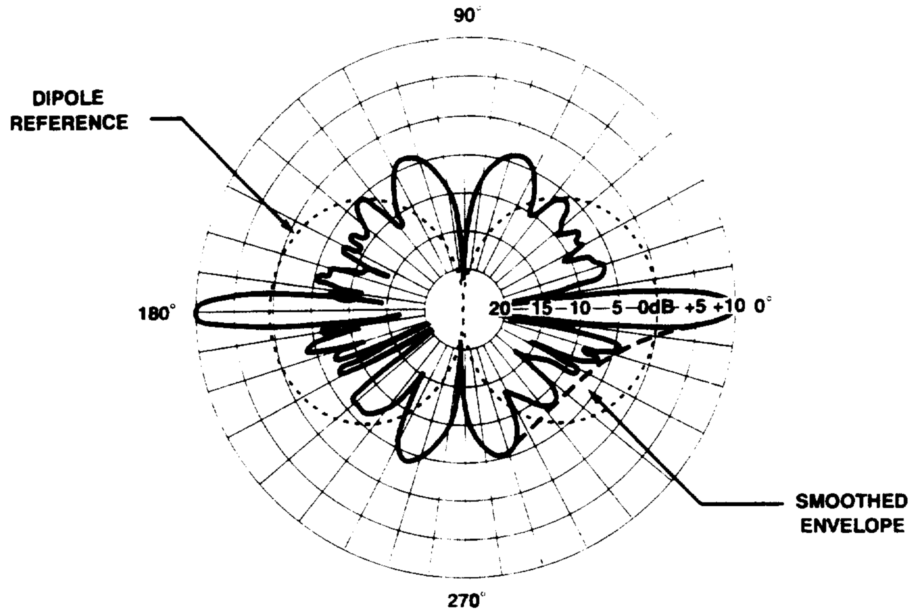

Fig 1. Typical 10-dB co-linear array vertical radiation antenna pattern used for cellular service. The vertical radiation pattern of the reference half-wave dipole is shown for comparison purposes as is the smoothed gain envelope commonly used when estimating exposure levels analytically.

The output of the test antenna was coupled to either a Hewlett-Packard (HP) 141T/8552B/8555A Spectrum Analyzer, an HP 8590A Spectrum Analyzer with an H-20 Counter Lock System, or a Singer Stoddart 37/57 Field Strength Meter. An HP 5343 Microwave Frequency Counter was used with the field-strength meter to provide a digital frequency readout. Occasionally, the measurements were made with both the spectrum analyzer (to locate active channels in real time) and the field strength meter (to measure the signal). In these instances, a 10-dB directional coupler was used to connect the test antenna to both instruments. Initially, the field strength meter was the instrument of choice for actually measuring the test-antenna output voltage, and the spectrum analyzer was the instrument of choice for identifying active channels. However, after numerous measured results obtained with each of the spectrum analyzers and the field strength meter were compared and found to be repeatable within approximately ±1 dB, the HP 8590A/H-20 system was used exclusively because of its portability and advanced features. This facilitated the measurement process because the scanwidth could be set to correspond to the block of frequencies used by the particular cellular telephone company (e.g., 880 to 890 MHz) and all active channels could be displayed and measured simultaneously. Also, this system capability of producing hard copy of the frequency/power spectra eliminated the need for manually recording the amplitude of as many as 14 channels at a single measurement point.

The spectrum analyzers and field strength meters are part of an automated data collection system installed in a mobile measurement van. This system can be programmed to scan over any desired band of frequencies between 10 kHz and 1 GHz. The antenna factors for the test antennas are stored in the software and the displayed data is the actual field strength of the incident fields. The van could not be used, however, because the selection criteria (e.g., flat, open accessible areas) limited the sites to towers located in fields, pastures, and other areas that were generally inaccessible to vehicular traffic. This restriction prohibited the direct use of the automated system: the spectrum analyzer, frequency counter and printer, or the field-strength meter and counter were removed from the van and operated manually. The AC power supply in the van was connected to the test equipment via a 60 m length of power cord. An advantage of this procedure is that it removed a large reflecting surface (the van) from the immediate vicinity of the test antenna, thereby minimizing a potential source of multipath interference. A disadvantage was the loss of automated data-collection capability. Even though the output of the spectrum analyzer could be stored for future analysis, or processed at the time of measurement by a personal computer (PC), there were practical limits to the amount of equipment that could be manually transported across fields and uneven terrain. As a result, the system most frequently used consisted of the HP (8590/H-20) spectrum analyzer, an HP 5386A Frequency Counter, a small printer, and the tuned dipole antenna.

Measurements were generally made at 3.05 m (10 ft) intervals along a radial extending from the fence that usually surrounds the tower and equipment building to the farthest practical distance. At each location, the test antenna was rotated to produce a maximal signal condition. Normally, measurements such as these require three orthogonal measurements [Tell and Mantiply, 1980; ANSI, 1981]. In this case, however, the polarization of the transmitting antenna was known and rotation of the test antenna in the vertical plane of the radial along which the measurements were being made was usually sufficient to quickly yield a maximum. The maximum generally occurred when the dipole axis was approximately perpendicular to a radial between the transmitting antenna and the test antenna or when the axis of the conical log-spiral antenna was parallel to the same radial. The 3 dB beamwidth of the test antennas was sufficiently broad that orientation was not crucial.

Once a maximum was obtained, the display data were downloaded to the printer and the location (distance) was recorded on the hard copy. The hard copy depicted the power spectra of all transmissions within the scanned band. The test antenna was then moved to the next location and the process repeated. The goal was to measure as many different channels as possible at each measurement point to average the effects of multipath interference and the frequency dependence of the side-lobe structure of the transmitting antenna. In some cases (e.g., service areas where cellular traffic density was low) only a few channels (including the setup channel) were active at any given time, regardless of how long one waited. In other cases, ten or twelve channels were usually active.

The electric-field strength N (in dB relative to 1 μV/m) was obtained from

$$N = C_L + A_F - P + 107$$

when the spectrum analyzer was used and from

$$N = C_L + A + N_F$$

when the field strength meter was used. C_l is the cable loss and A_F is the antenna factor (both in dB). P is the power measured at the input terminals of the spectrum analyzer (in dBm), 107 is a constant of proportionality (for a 50 ohm system) between power expressed in dBm and voltage in dBμV. and N_F is the voltage measured at the input terminals of the field-strength meter (in dB relative to 1 μV/m). Plane wave conditions prevailed at each measurement point and the corresponding power density, S, for each of the separate channels was obtained from the relationship between the wave impedance (377 Ω) and the square of the electric field strength, that is,

$$S = E^2 / 377 \qquad \mathrm{W/m^2}$$

The arithmetic mean of the power density for the total number of channels measured at each point (including the setup channel) was obtained, and these results are shown in Figures 2–5. The measured power density of each channel is depicted by solid circles and the per channel mean value by the solid line. The vertical lines drawn from the lowest to the highest power density measured at each point indicate the range of the data.

As can be seen in the figures, the difference between the lowest measured level and the highest at times exceeds 10 dB, particularly in the nulls. The ERP of each voice channel was usually the same (i.e., 100 W), and the ERP of the setup channel was typically 50 W. (The lowest value at each measurement point is usually the setup channel, which transmits continuously and was always measured.) The differences in signal strengths of the different channels can be attributed to the frequency dependence of the antenna

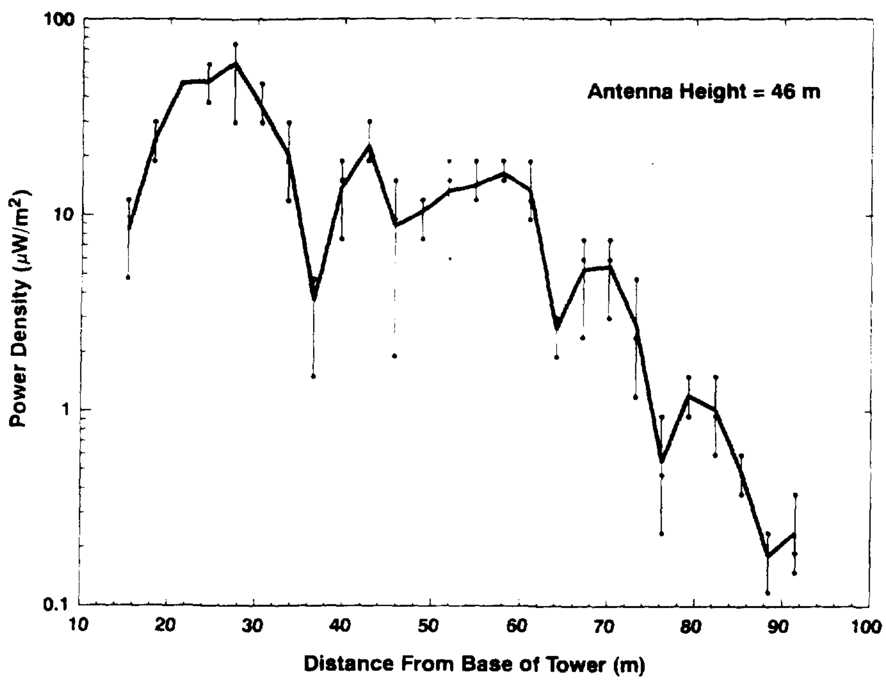

Fig. 2. Mean power density per channel measured 2 m above grade along a radial extending from the base of a monopole-type cellular antenna tower 46 m high. The maximal measured value for a single channel is approximately 80 μW/m², which occurs 26 m from the base of the mast. Each solid circle is the measured value of a discrete radio channel

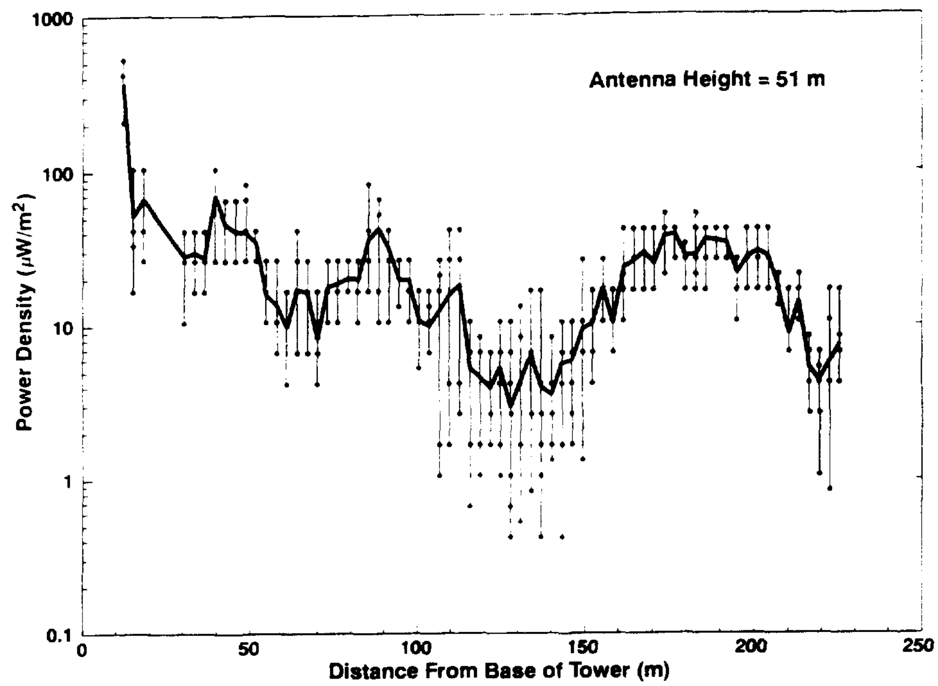

Fig. 3. Mean power density per channel measured 2 m above grade along a radial extending from the base of a monopole type cellular antenna tower 51 m high. The maximal measured value for a single channel is approximately 500μW/m², which occurs approximately 12 m from the base of the tower and approximately 1 m from the surrounding fence. At points removed from reflecting surfaces, the maximal measured value is less than 100 μW/m². Each solid circle is the measured value for a discrete radio channel.

radiation pattern, particularly at angles at which the lobes are relatively narrow and the nulls deep, and to the effects of multipath interference.

With the exception of the 200–500 μW/m² values measured at a distance of approximately 10 m from the 51 m monopole (Fig. 3), the maximal power density per channel was found to be about 100 μW/m² or less, for all four towers. The 500 μW/m² value shown in Figure 3 was measured approximately 1 m from the chain-link fence surrounding the facility and approximately 3 m from nearby parked automobiles, and could be due to multipath interference. Measurements made within 1 m from a similar fence approximately 100 m from the tower did not produce similar high readings.

Initially, more convenient measurement techniques were evaluated—that is, techniques that did not require manually moving AC operated equipment across fields and pastures. For example, the per-channel mean shown in Figure 5 for distances between 25 and 80 m was obtained using a Holaday Industries (HI) Model HI 3001 Broadband Isotropic Field-strength Meter with a high-sensitivity electric-field probe (Model HSE). The minimal discernible level of the HI 3001/HSE is about 300 μW/m². For these measurements, the probe was set at a height of approximately 2 m and a tuned dipole, connected to a spectrum analyzer via 12.2 m of cable (Storm Series 90), was positioned at the same height about 1 m from the HSE probe. The

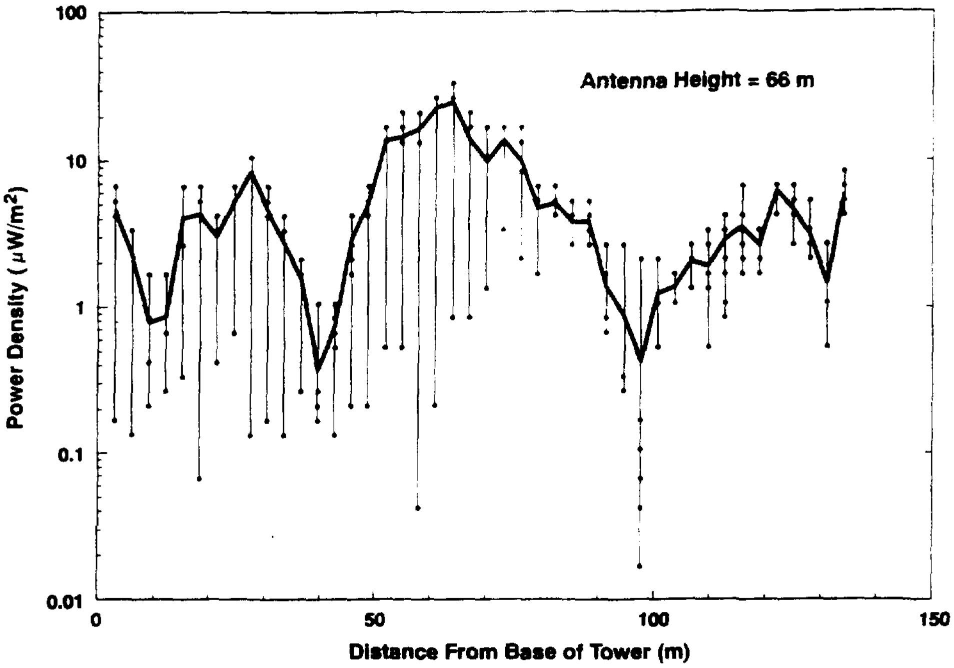

Fig. 4. Mean power density per channel measured 2 m above grade along a radial extending from the base of a lattice-type cellular antenna tower 66 m high The maximal measured value for a single channel is less than 35 $\mu W/m^2$, which occurs 65 m from the center of the base of the tower. Each solid circle is the measured value for a discrete radio channel.

scanwidth of the spectrum analyzer was adjusted to display the block of transmitter frequencies used at that site. Simultaneous measurements were made with the broadband instrument and the spectrum analyzer. The total power density of all cellular channels active at the time of measurement was computed as above and compared with the corresponding reading that was indicated on the broadband instrument. The difference was considered the local background in the absence of the cell-site transmissions. This procedure was repeated at several locations to determine the relative variability of the electromagnetic background, which was found to be relatively constant. From the first measurement point, the broadband probe was moved in increments of approximately 3 m along a prescribed radial and a measurement was made at each point. Simultaneously, the spectrum analyzer and dipole, which were not moved, were used to count the number of active transmitting channels. The temporal and spatial characteristics of the electromagnetic background were assumed to remain constant. The data in the figure correspond to the reading indicated by the broadband instrument, minus the value considered background (as obtained from the procedure described above), divided by the number of active transmitting channels. This technique works satisfactorily provided the signal levels are of the order of 300–500 $\mu W/m^2$, or greater, and the spatial and temporal characteristics of the electromagnetic background are relatively constant.

Other broadband techniques that were tried included the use of the Holaday 3001/HSE instrument with a datalogger (a device that samples the recorder output

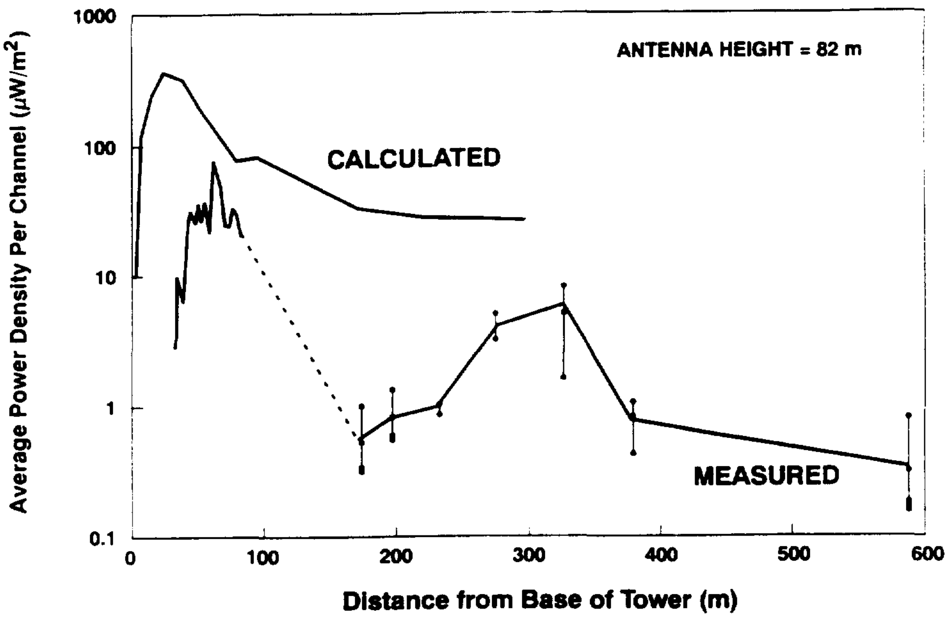

Fig. 5. Mean power density per channel measured 2 m above grade along a radial extending from the base of a lattice-type cellular antenna tower 82 m high. The maximal measured value for a single channel is approximately 80μW/m², which occurs 60 m from the center of the base of the tower. Each solid circle is the measured value for a discrete radio channel. Also shown are the corresponding values obtained from the free-space transmission formula using the smoothed antenna pattern and the assumption of perfect ground reflection.

of the electric-field probe at a rate of once per second and stores the data for off-loading into a PC for analysis and graphical display). In this case, the averaging time of the datalogger was set equal to the sampling rate (once per second) and the surveyor walked at a constant pace along a radial from the base of the tower to as far as practical. The measured path length and the corresponding number of frames recorded by the datalogger as the path was transversed were used to obtain the spatial distribution of the fields along the path. This process was conducted several times along one path, first in one direction, then in the opposite, and then the results were compared. Unfortunately, the measured levels were not much greater than the minimal discernible level of the instrument and artifactual data associated with electrical noise (resulting from cable flexure, etc.) yielded output data that were not repeatable with sufficient accuracy to render this a useful technique.

For purposes of comparison, the per-channel power density for the 82 m high antenna tower was calculated using the free-space transmission formula

$$S = \frac{PG}{4\pi r^2}$$

where S is the power density in W/m², P is the antenna input power in watts, G is the antenna gain (relative to an isotropic radiator) in the direction of interest, and r is the distance in meters from the antenna to the point in question. For this example, the radiation-pattern envelope (smoothed antenna pattern) shown in Figure 1 was used and perfect reflection from the ground was assumed. The latter increases the value predicted by the above equation by a factor of four times. An ERP of 100 W (the product of the antenna input power and the gain relative to that of a half-wave dipole, i.e., 10 dB) was also assumed, resulting in an antenna input power of 10 W and an antenna gain, referenced to an isotropic radiator, of 12.15 dB.

As can be seen in Figure 5, the above technique considerably overpredicts power-density levels, particularly in the regions of the nulls of the antenna pattern. This excess also has been found to be the case when similar measurements were made in the vicinity of microwave aperture-antennas [Petersen, 1979, 1980]. In part, this excess can be attributed to the use of a smoothed antenna pattern (see Fig. 1) for the analysis, in part to the assumed, perfect ground reflection, and in part to the particular site, which because of its height, may have been operating at an ERP below 100 W. (Unless lower power is used, the signals from antennas that are exceptionally high to clear local terrain can cause interference in remote cells that operate at the same frequencies.) For hazard assessment, however, the error associated with commonly used analytical techniques has always been found to be in the direction of conservatism.

ROOFTOP ANTENNA MEASUREMENTS

In many cases omnidirectional antennas are mounted on roofs of buildings, usually on parapets surrounding penthouses or equipment rooms. Frequently, the bottom of the radiating portion of the antenna is at head height for someone standing on the roof, and the question of exposure of such individuals becomes important. To address this issue in a pragmatic manner, measurements of the plane-wave-equivalent power density were made in the near field and the far field of a typical cell-site antenna that was mounted on the flat roof of the AT&T Bell Laboratories location in Whippany, NJ. (See Fig. 6 for a physical layout of the roof and the grid used for the rooftop antenna measurements.) Two separate sets of measurements were made: measurements along thirteen vertical paths, each path parallel to the antenna axis, at distances from approximately 0.7 m to 13.5 m from the antenna; measurements along radials in a horizontal plane through the center of the radiating portion of the antenna, and along radials in a horizontal plane approximately 0.15 m below the lowermost radiating element. The latter measurements were made at distances between approximately 15 and 55 m from the antenna.

Near-Field Measurements

The cell-site antenna was an omnidirectional (in the horizontal plane) co-linear array, with a gain of approximately 9 dB relative to that of a half-wave dipole (similar to Decibel Products DB809). The center of the radiating portion of the antenna was 4.4 m above the plane of the roof and the lower and upper ends of the radiating portion of the antenna were, respectively, 2.9 and 5.1 m above the same plane. The measurements were made with six or seven transmitters operating simultaneously, each at a different frequency between 880 and 890 MHz. Forward and reverse power levels were measured at each frequency with RF power meters and a bidirectional coupler located at the antenna input port. The measured data were normalized to cor-

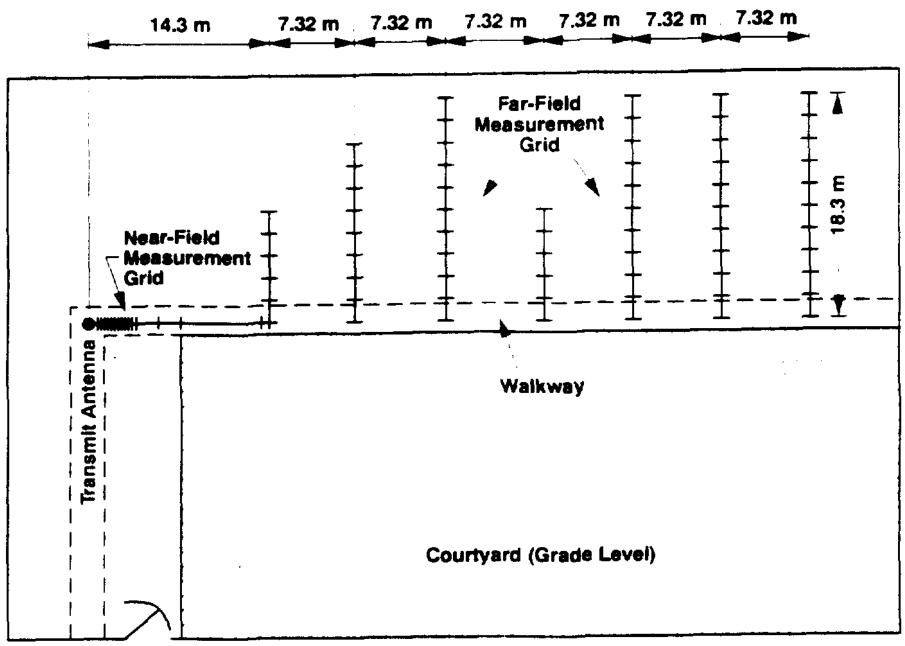

Fig. 6. Plane view of the roof and the grid used for rooftop measurements. The path marked "near-field" was used to make the measurements along 13 vertical cuts with a broadband probe. The paths separated by 7.32 m were used for the narrowband measurements, which were made at 1.83-m intervals along each path.

respond to 16 transmitters, each with an ERP (relative to a half-wave dipole) of 100 W—that is, typical cell-site parameters.

Several sets of measurements were made along vertical paths parallel to the antenna axis using a Narda Broadband Isotropic Radiation Monitor, Model 8316/8321. The Narda instrument was fixed to a horizontal dielectric support, approximately 1 m in length, that could be raised and lowered along a vertical wooden mast approximately 5.5 m long. The axis of the probe handle was oriented horizontally with the sensing antennas closest to the cell-site antenna. The electronics package was located at the opposite end of the cross-piece. The mast was mounted to a moveable base. The vertical column had graduation marks every 0.15 m (6 inches), from top to bottom. Thus, the elevation of the probe could be repeatedly set at discrete known elevations referenced to the plane of the roof. The meter readings were obtained remotely with the aid of a 20X telescope. The measurements were made starting at the highest point (4.9 m) and the probe was sequentially lowered in 0.15 m increments. Zero-drift of the instrument was a problem even after the instrument was operated for a considerable time before data were taken. Because of this, zero-drift was checked at the lowermost measurement point of each traverse by quickly shielding the probe in copper foil. Any run where the drift was greater than 5 percent of full scale (100 mW/m^2) was repeated. All measurements were made with either the 0–2 or the 0–20 W/m^2 (0–0.2 or the 0–2 mW/cm^2) scales. The results of these measurements are shown in Figures 7 and 8. As shown, the measured values have been

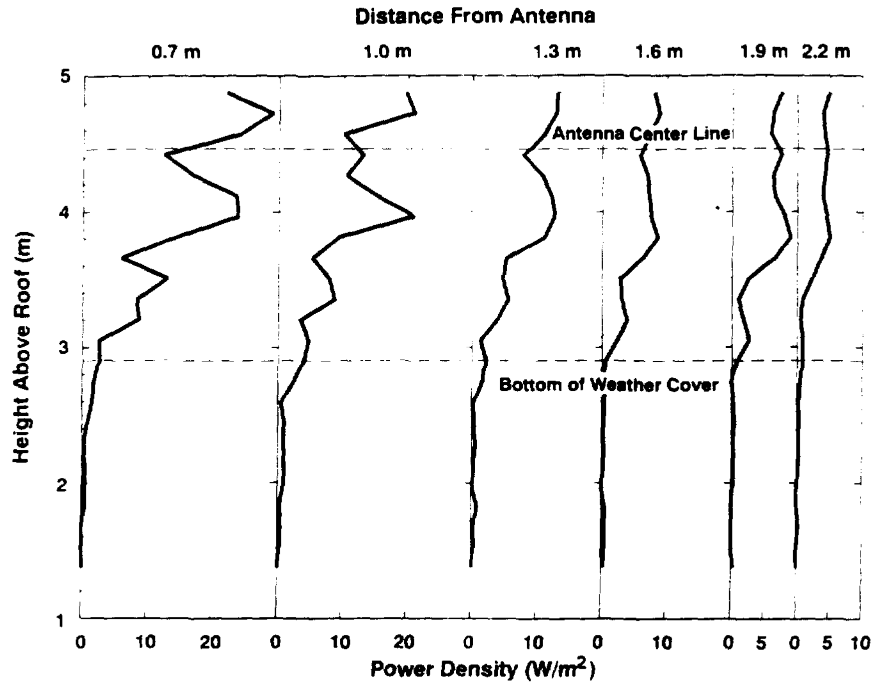

Fig. 7. Measured power density along vertical cuts (0.7–2.2 m) in the near-field of a 9 dB co-linear array. The data were normalized to 16 transmitters. The radiating portion of the antenna starts approximately at the bottom of the weather cover.

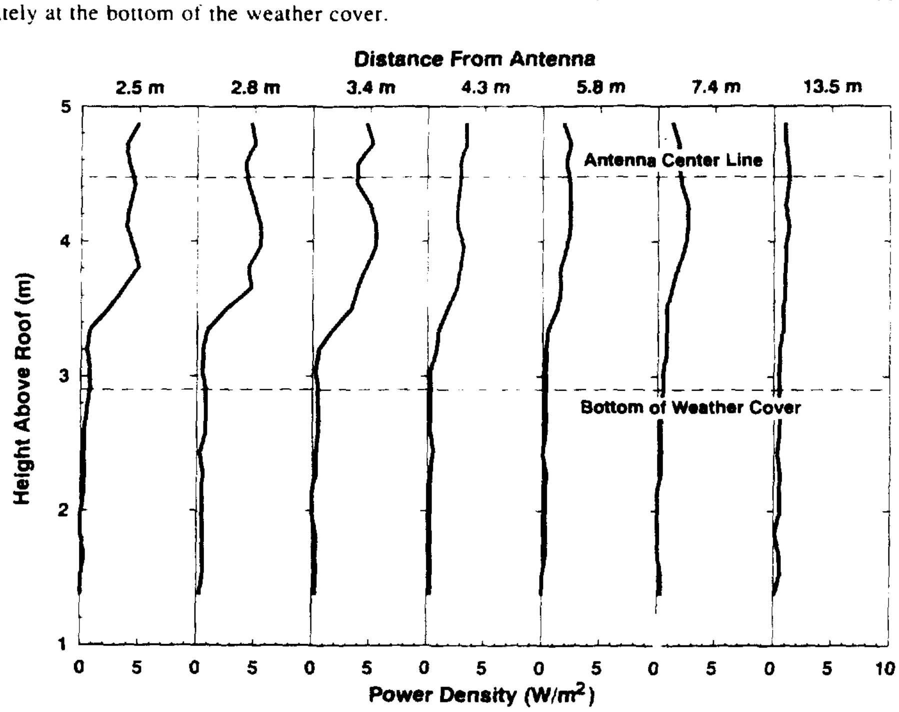

Fig. 8. Measured power density along vertical cuts (2.5–13.5 m) in the near-field of a 9-dB co-linear array. The data were normalized to 16 transmitters. The radiating portion of the antenna starts approximately at the bottom of the weather cover.

normalized to correspond to 16 transmitters, each operating at an ERP of 100 W relative to a half-wave dipole.

As indicated in the figures, the maximal power density normalized to 16 transmitters is approximately 30 W/m^2. This value occurs at points slightly above and slightly below the centerline of the radiating portion of the antenna. As the distance from the antenna increases, the peaks smooth somewhat as the main beam begins to form. Part of the smoothing can also be attributed to the lack of sensitivity of the broadband probe at the greater distances. At head height (approximately 1.8 m) the power density for this mounting configuration is below 1 W/m^2 everywhere.

Far-Field Measurements

A second set of measurements was made at distances between approximately 15 and 55 meters from the same rooftop antenna. Rather than making the measurements along a single radial, a 7.32 × 1.83 m grid was laid out and measurements were made at each intersection (see Fig. 6). Two sets of measurements were made: the first set with the test antenna at a height of approximately 2 m above the roof level (i.e., approximately head height) the second set with the test antenna at a height of approximately 3.8 m (i.e., in the horizontal plane through the center of the radiating section of the antenna, or beam center).

The measurements were made using a 1–10 GHz conical log-spiral antenna (Singer Stoddart Model 93491-2) and a Singer Stoddart Model 37/57 Field Strength Meter. The antenna was calibrated in a known, linearly polarized (vertical) field. As above, six or seven channels were operating, and the antenna input power at each frequency was determined from the forward and reflected powers measured with two power meters and a dual directional coupler located at the antenna input port. All measured data have been normalized to correspond to 16 radio channels, each operating at an ERP of 100 W relative to a half-wave dipole.

The results of the measurements made at a height of approximately 2 m are shown in Figure 9. Also shown are a few of the corresponding near-field values, measured as described above by the broadband probe (from Figs. 7 and 8). The solid

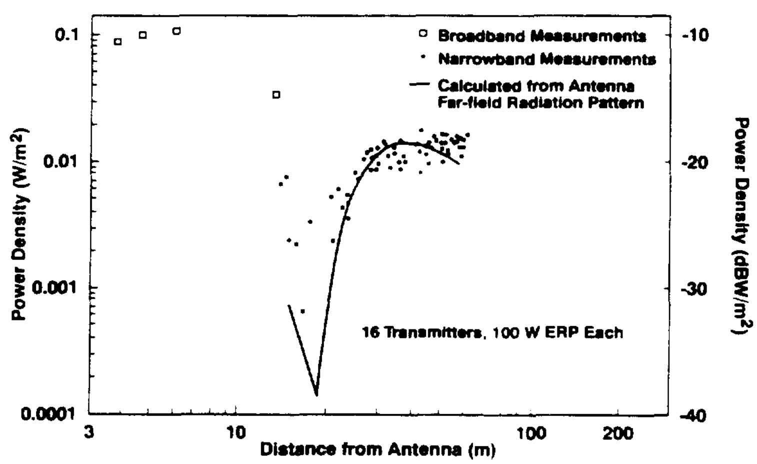

Fig. 9. Narrowband and broadband power density measurements at a height of approximately 2 m above the plane of the roof. The centerline height of the radiating portion of the antenna is approximately 4.5 m above the plane of the roof. The broadband measurements are taken from Figs. 7 and 8.

line is the value predicted from the antenna far-field radiation pattern. The actual radiation pattern of the antenna was used for these calculations, not the smoothed envelope, and reflections from the ground were assumed to be zero. The notch is between the main beam and the first side lobe of the antenna pattern.

As can be seen in Figure 9, the measured values are both above and below the predicted values at the edge of the main beam, but generally by less than 3 dB. The differences can be attributed to several factors, including the analytical value was obtained from an antenna pattern measured at a single frequency, whereas the measurements were made at several frequencies (spaced between 880 and 890 MHz); the far-field antenna gain was used; and the theoretical values do not take into account scattering from the surface of the roof. Generally, when hazard analyses are performed, perfect reflection is assumed and a factor of four times (6 dB) is used to account for the possibility of in-phase addition of the electric field. If perfect reflection was assumed here, the predicted values would be conservative with respect to the measured values.

The results of the measurements made in the horizontal plane through the center of the main beam are shown in Figure 10. Also shown in the figure are the corresponding near-field values as measured with the broadband probe. As can be seen in the figure, the near-field values decrease approximately linearly with distance (approximately 3.3 dB/octave or 11 dB/decade), but the far-field values decrease inversely with the square of the distance (6 dB/octave or 20 dB/decade). The solid line parallel to the narrowband measured values is the analytical value corresponding to an ERP 1600 W (16 transmitters) as determined from the far-field antenna pattern and the free-space transmission formula. This curve intersects the dashed line drawn parallel to the measured near-field values at a distance of approximately 9 m. This would indicate that for purposes of hazard analyses, the far-field antenna pattern for this and similar antennas can be used at distances as close as 9 m with reasonable accuracy even though conventional theory would predict a far-field distance of approximately 60 m [Jasik, 1961].

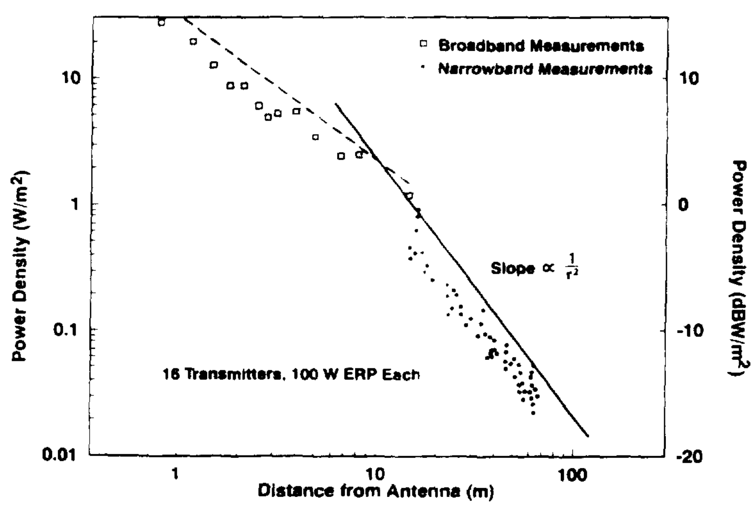

Fig. 10. Narrowband and broadband measurements at the centerline height of the radiating portion of the roof-mounted antenna (approximately 4.5 m above the plane of the roof).

CONCLUSIONS

Electromagnetic fields near the base of typical antenna towers used for cellular telephone service, and in the near-field of commonly used antennas that are frequently mounted on roofs of buildings, have been characterized. Although the omnidirectional antenna was chosen for this study, the results for sector antennas mounted at the same height on a tower would not be expected to differ significantly on a per channel basis because the antenna patterns are similar. With respect to antennas mounted on buildings however, the omnidirectional antenna, when compared with sector antennas, probably represents more of a worst-case scenario with respect to potential exposure. This is because omnidirectional antennas are frequently mounted in a manner such that the center of the radiation pattern is only a few feet over the head of someone standing on the building roof, or on the roof of equipment rooms or penthouses, whereas sector antennas are typically mounted to the sides of buildings where the main beam is inaccessible in the near field.

The results of these measurements indicate that the maximal power density in the vicinity of typical towers ranging in height from 46 m (most common) to 82 m is less than 100 $\mu W/m^2$ (10 nW/cm^2) per channel (transmitter) except in proximity to large metallic surfaces near the base of the tower. Thus, for a 96-channel system operating at an ERP of 100 W per channel, the aggregate maximum power density would be less than 10 mW/m^2 (1 $\mu W/cm^2$). It was also found that, as expected, conservative techniques normally used for analytical hazard analyses overpredict the strengths of the actual fields.

Similarly, the power density in the main beam of a typical omnidirectional antenna used for cellular service was found to be less than 30 W/m^2 (3 mW/cm^2) at distances greater than 0.7 m from the antenna, less than 1 W/m^2 (100 $\mu W/cm^2$) at distances greater than approximately 12 m, and less than 0.1 W/m^2 (10 W/cm^2) at distances greater than approximately 50 m. These values are normalized to 16 transmitters, each with an ERP of 100 W. A comparison of the results of these measurements with the analytical values obtained from the free-space transmission formula (based on the antenna far-field pattern) indicates that the analytical values exceed the predicted values (by less than 3 dB) at distances greater than approximately 10 m. For purposes of hazard analyses of similar antennas at distances between 1 and 10 m, the maximal power density can be estimated from

$$S = \frac{0.02\,N\,(ERP)}{r}$$

where S is the power density in W/m^2, N is the number of channels, ERP is the effective radiated power in watts referenced to a half-wave dipole, and r is the distance in meters. (The above empirical equation, with power density inversely proportional to distance, was derived from the results of the measurements made in the horizontal plane through the center of the main beam.)

The power density measured at head height (approximately 2 m above the plane of the roof was found to be less than 1 W/m^2 (100 $\mu W/cm^2$) everywhere, less than 200 mW/m^2 (20 $\mu W/cm^2$) at distances greater than 3 m, and less than 20 mW/m^2 (2 $\mu W/cm^2$) at distances greater than 20 m.

The above values can be compared with current exposure limits and recommendations such as those of IEEE C95.1-1991 [IEEE, 1991] (a revision of ANSI

C95.1-1982 [ANSI. 1982]) and NCRP Report 86 [NCRP. 1986]. A comparison of the above values with the 29–30 W/m^2 limits for the controlled environment [IEEE. 1991] or for occupational exposure [NCRP. 1986], which would be appropriate for telephone craft working on a roof or on the platform of a tower. indicates that the limits could be exceeded only at distances (in the main beam) closer than 0.7 m. However, if several antennas are located in proximity (e.g., on a tower platform) such that the bottom of the radiating portion of the antenna is approximately head height, it may be possible to exceed the above limits and appropriate work practices should be implemented. For public exposure (uncontrolled environment), the NCRP and IEEE exposure limits are approximately 6 W/m^2 at frequencies between 870 and 890 MHz. A comparison of the above values with this limit indicates that the fields associated with a 16-channel, 100-W ERP omnidirectional antenna exceed the public exposure recommendations only at distances closer than 3 m. The levels measured near the base of typical towers used for cellular-radio cell-site antennas indicate that the maximal combined power density corresponding to 96 transmitters operating simultaneously, each at an ERP of 100 W, is about 10 mW/m^2 (1 $\mu W/cm^2$). This power density is well below the above limits for the uncontrolled environment.

ACKNOWLEDGMENTS

The authors thank Mr. W. Kuhlmann of AT&T Bell Laboratories (retired) with whom the rooftop measurements were made and Mr. L. Faiella of Bell Atlantic Mobile Systems, who located the cell-site antenna towers and coordinated the site visits.

REFERENCES

ANSI (1981): "Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave." New York: American National Standards Institute.

ANSI (1982): "Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields—300 kHz to 100 GH." New York American National Standards Institute.

IEEE (1991): "Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz." Piscataway, NJ Institute of Electrical and Electronics Engineers.

Jasik H (1961): Fundamentals of antennas. In Jasik H (ed): "Antenna Engineering Handbook." New York: McGraw-Hill pp 2.14–2.15.

NCRP (1981): "Radiofrequency Fields—Properties, Quantities and Units, Biophysical Interaction, and Measurements." Bethesda, MD: National Council on Radiation Protection and Measurements.

NCRP (1986): "Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields." Bethesda, MD: National Council on Radiation Protection and Measurements.

Petersen RC (1979): Levels of electromagnetic energy in the immediate vicinity of representative microwave relay towers. In: "Proceedings of the International Conference on Communications—Boston, MA (June 10–14, 1979)." IEEE NY. pp 31.5.1–31.5.5.

Petersen RC (1980): Electromagnetic radiation from selected telecommunications systems. Proc of the IEEE 68:21–24.

Shinn DH (1976): Avoidance of radiation hazards from microwave antennas. Marconi Rev (G.B.) 39:61–80.

Stuchly MA (1977): Potentially hazardous microwave radiation sources—a review. J Microwave Power 12:369–381.

Tell RA, and Mantiply, ED (1980): Population exposure to UHF and broadcast radiation in the United States. Proc of the IEEE 68:7–72.

TAB D

Microwave Radio Fact Sheet

What are Microwaves

The term "microwave" is the name given to a small portion of the entire electromagnetic spectrum. The electromagnetic spectrum is the range of some characteristic of electromagnetic waves and is usually arranged in sequential order of that component, for example frequency or wavelength. (See EEPA Fact Sheet #1.) In order of increasing frequency, the electromagnetic spectrum contains radiowaves, infrared radiation, visible radiation (light), ultraviolet radiation and, at much higher frequencies, the more energetic forms of radiation, for example, X-rays and cosmic radiation. The microwave region lies in the upper part of what is generally known as the radiofrequency portion of the spectrum and below the infrared region. The term "microwave" is, thus, the nomenclature for a particular region of the electromagnetic spectrum, *i.e.*, high-frequency radiowaves. It is not a unique form of radiation. The only difference between microwave radiation and infrared radiation or light, *etc.*, is the frequency.

There are different definitions of the "microwave band" of frequencies. For example, the Federal Communications Commission (FCC) considers the lower frequency end of the microwave band to start at a frequency of 890 million cycles per second, or 890 megahertz (MHz); The Institute of Electrical and Electronics Engineers considers the microwave frequencies to start at approximately 1000 MHz. Others consider microwaves as the frequency band extending from 300 MHz to 300 billions of cycles per second, or 300 gigahertz (GHz). In accordance with the last definition, examples of microwave technology include certain conventional mobile radio-telephones, all cellular radio-telephones, all television broadcast channels above channel 13, satellite communications systems, certain walkie talkies, circuits for high-speed computers, almost all radars, certain navigational systems, point-to-point microwave radio, certain anti-theft detectors and intrusion alarms, certain amateur radio systems, certain diathermy units, local area networks in offices for communicating between computers, plus countless other familiar products and devices including microwave ovens.

The first person of record who intentionally generated electromagnetic energy at microwave frequencies was H. R. Hertz who, during the latter part of the last century, carried out experiments to confirm the existence of electromagnetic waves as postulated by James Clerk Maxwell some 30 years earlier [1]. By 1900 experimenters had generated frequencies above 15 GHz and by 1920 frequencies above 3700 GHz. These experiments, however, produced energy at low levels and could not be controlled readily. Major breakthroughs and developments in microwave technology occurred during World War II as means were sought for generating the higher frequencies necessary for the development of smaller radars for installation in airplanes, and for the improvement of the resolution of existing search and fire-control radars.

Development of Microwave Relay

A characteristic of electromagnetic energy is that at sufficiently high frequencies, energy can be propagated in a narrow, well-collimated beam, from a reasonable size antenna. By taking advantage of this characteristic, radio systems can be designed to propagate energy from point-to-point very efficiently. One of the first uses envisioned for a system such as this was as a replacement for the wire-pairs and cables used for the transmission of long distance telephone traffic.

In 1931, the first microwave (called "microray" at the time) radio link for telephone traffic was established between Dover, England and Calais, France [1]. A few years later, Bell Laboratories established microwave radio links between buildings in New York. Although work was carried out at Bell Laboratories in the late 1930's toward the development of a microwave radio relay system to be used for long distance telephone traffic, most of this work was sidetracked by the war effort. Toward the end of the war, work on microwave radio resumed at Bell Laboratories and many other companies and in 1947, the first point-to-point microwave radio relay system went into service between Boston and New York City. By 1951 the first coast-to-coast system went into operation.

The system is referred to as "radio relay" because radio signals are received, amplified and retransmitted (relayed) from station to station in a straight line-of-sight path. That is, the stations form a chain with each station receiving, amplifying and retransmitting the signal to the next station. For long distance telephone traffic the stations are usually located 20-30 miles apart; for other services the stations may be much closer. A typical station would consist of a small building, or a room which houses the radio receivers, transmitters, and the necessary switching equipment. The receivers and transmitters are connected to antennas, sometimes in the shape of a dish, located on a tower or on the roof or sides of buildings. Sometimes a single antenna is used for both transmitting and receiving. Many times separate transmitting and receiving antennas are used and frequently two receiving antennas located at different heights are used.

By 1980 there were approximately 22,000 licensed microwave-radio stations in the US and, presently, there are well over a hundred thousand microwave stations in operation. Microwave relay systems range from small privately owned systems to large systems such as those operated by the telephone companies. A small station may have a single receiver and transmitter. A large station may have several hundred receivers and transmitters plus a number of antennas. Microwave radio is used not only by telephone companies for transmission of voice and data, but is used extensively by corporations, the federal government, municipal governments, schools, television broadcast stations, utilities, hospitals, *etc.*, wherever a need exists for a private communication or data link. One merely has to look at the number of "dish" antennas on the roofs of buildings in various metropolitan areas to realize the ubiquity of microwave radio.

Environmental Levels Near Microwave Radio-Relay Installations

In spite of the number of microwave radio relay stations in operation, exposure of the public and the worker to microwave energy is practically negligible. This is because microwave radio operates at very low power levels when compared with other, more familiar types of radio services. The output power of a typical transmitter used for microwave radio is a few watts or less, similar to that of a CB or cellular mobile radio. Even when a number of transmitters are coupled to a single antenna, the total radiated power is well below one hundred watts and in many cases is less than one watt. Moreover, the energy is propagated from antennas (specifically developed for microwave relay transmission) in a very narrow or focused beam (similar to that of a searchlight). Finally, in order for the system to function properly, a clear, unobstructed line-of-sight path must exist between the transmitting antenna located at one station and the receiving antenna at the next. Thus, buildings, homes, and hence, people cannot be located in the path of the beam near the transmitting antennas.

During the late 1970's and early 1980's measurements made in the vicinity of a large number of "microwave towers" and on the rooftops of buildings near microwave antennas indicated that with few exceptions (the exception being locations directly under the beam path near the base of a microwave tower or directly below a roof-mounted antenna), the levels of electromagnetic energy to which the public is exposed are not distinguishable from the reported ambient background of approximately 0.005 $\mu W/cm^2$ [2,3]. Even in the exceptional cases the measured levels of microwave energy were found to be thousands of times below exposure limits commonly used in the US, such as those developed by ANSI [4], IEEE [5], NCRP [6], commonly used international standards such as those proposed by IRPA/INIRC [7] and, in fact, were found to be lower than any exposure limits used anywhere. Because of the low power used, the levels directly in front of most antennas used for microwave radio are substantially below the exposure limits commonly used in the US.

Conclusion

With respect to a concern about exposure to electromagnetic energy from microwave radio, conclusions reached by the FCC address the issue explicitly. When implementing the National Environmental Policy Act regarding potentially hazardous RF radiation from radio services which they regulate, the FCC categorically excluded microwave radio relay, from hazard analyses because "individually or cumulatively they do not have a significant effect on the quality of the human environment" [8].

References

1. E. F. O'Neill (Ed.), *A History of Engineering and Science in the Bell System - Transmission Technology (1925-1975)*, AT&T Technologies, Indianapolis, IN. (1985)

2. R. C. Petersen, "Levels of Electromagnetic Energy in the Vicinity of Representative Microwave Relay Towers," In: *Proceedings of the International Conference on Communications - Boston, MA, (June 10-14, 1979*, IEEE, NY. (1979)

3. R. C. Petersen, "Electromagnetic Radiation from Selected Telecommunications Systems, Proceedings of the IEEE, Vol. 68, No. 1. (1980)

4. ANSI - American National Standard *Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 300 MHz to 100 GHz*, ANSI C95.1-1982, American National Standards Institute, New York, NY. (1982)

5. IEEE - Transnational Standard *Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, C95.1-1991, IEEE, Piscataway, NJ. (1992)

6. NCRP - *Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields*, NCRP Report No. 86, National Council on Radiation Protection and Measurements, Bethesda, MD. (1986)

7. International Radiation Protection Association International Non-Ionizing Committee (IRPA/INIRC), "Interim Guidelines on Limits of Exposure to Radiofrequency Electromagnetic Fields in the Frequency Range from 100 kHz to 300 GHz," *Health Physics*, Vol. 46, No. 4. (1984)

8. Action by the Commission, February 12, 1987, by Second Report and Order (FCC 87-63), and Third Notice of Proposed Rulemaking (FCC 87-64). General Docket No. 79-144.

TAB E